

Technology Requirements for Guided Stratospheric Balloons

M. K. Heun, K. T. Nock, A. A. Pankine
Global Aerospace Corporation
711 W. Woodbury Rd., Suite H
Altadena, CA 91101

Abstract - We report on the progress towards the development of technology requirements for the new class of stratospheric balloons being developed by NASA. The guided stratospheric balloons offer new potential science capabilities and extend capabilities of the existing observing platforms. Some of these new capabilities include: regional or global measurements; a few to many years of flight duration; trajectory control; remote and *in situ* sensing throughout the atmosphere; and adaptive sampling. These new systems may have potential applications in many research areas: global climate change, Earth radiation balance, atmospheric chemistry, and solid Earth monitoring. We discuss (a) potential future Earth science applications and (b) the set of requirements driving the development of future balloon platform technologies.

I. INTRODUCTION

Part of the “Vision” activity of NASA’s Earth Science Enterprise (ESE) is to develop concepts and plans for platform technologies to be pursued and developed in the future. One potential platform for Earth Science is very long life, guided stratospheric balloons. The NASA Earth Science Technology Office (ESTO) has solicited input from Earth scientists via a small study activity that seeks to identify technology requirements for future stratospheric observing platforms. Global Aerospace Corporation (GAC) is leading this study to (1) explore Earth science applications for ultra long life stratospheric balloons; (2) develop a set of driving Earth science requirements for stratospheric balloons; (3) identify technology needs for stratospheric balloon platforms to meet these requirements, and (4) develop a preliminary roadmap for such technology development including technology readiness levels (TRLs) and need dates. This paper gives an overview of the first two activities for this study: we discuss potential future Earth science applications and the set of requirements driving the development of future balloon platform technologies.

The new class of stratospheric balloons being developed by NASA offers new potential science capabilities and extends capabilities of the existing observing platforms. Some of these potential capabilities include: regional or global measurements; a few to many years of flight duration; trajectory control; remote and *in situ* sensing throughout the atmosphere; and adaptive sampling. These new systems may have potential applications in many research areas: global climate change, Earth radiation balance, atmospheric chemistry, and solid Earth monitoring.

New technologies would need to be developed to fully utilize the potential capabilities of new platforms. Plans for technology development need to be made so that crucial

technologies are not overlooked and efforts are concentrated on the development of the most important technologies. The first step in identifying technology requirements is to obtain science input from potential users of these platforms – the scientists. For this purpose ESTO and GAC organized an informal workshop where scientists, loosely divided into three groups: surface science, atmospheric chemistry and atmospheric radiation, - were presented with a summary of current state of the art in balloon technology and potential future capabilities of stratospheric balloons. The scientists were then asked to outline a potential earth science application for future balloon platform that would help to answer key questions outlined in the NASA ESE Strategic Plan. The scientists also described the measurements and instrumental approaches for these applications, and the requirements that these measurements and instrumental approaches impose on the observational platform. From the set of these requirements GAC will develop the set of technology requirements. The rationale behind technology requirements development is illustrated on Fig. 1.

The following sections describe in more detail the Earth science applications that were considered for this study and the set of requirements that was eventually developed. The measurement and instrument requirements are summarized in Table I and Table II of the Appendix, respectively.

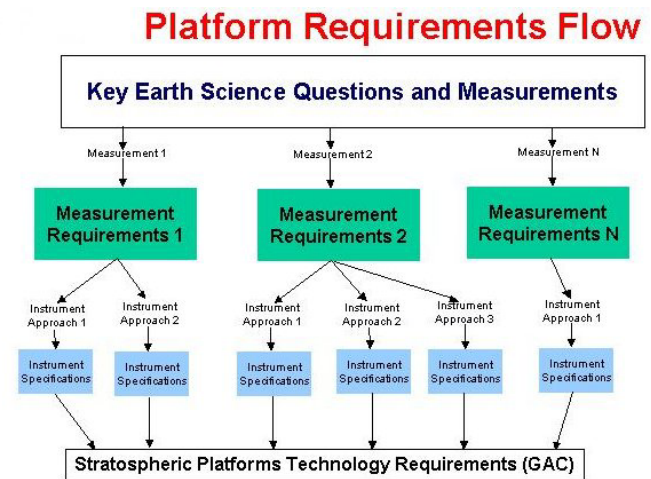


Fig. 1. Rationale behind technology requirements development

II. EXAMPLE EARTH SCIENCE APPLICATIONS

This section gives an overview of Earth Science applications that were used to form the set of requirements.

A. Surface Science (SS)

SS1) Height Changes of the Ice Sheet Surface

Stratospheric balloon platforms can be utilized to measure the changes in the height of the ice sheet surface from stratospheric altitudes. The candidate regions for this mission are the Antarctic ice sheet, the Greenland ice sheet, or any other ice cap. Current approaches to the ice topography measurements include spacecraft (for example, ICESat/GLAS - Geoscience Laser Altimeter System, CryoSat, MOLA - Mars Orbiter Laser Altimeter, currently around MARS on Mars Global Surveyor), aircraft (NASA's ATM - Airborne Topographic Mapper), and surface measurements. Stratospheric balloons offer an inexpensive alternative to these approaches. Balloon measurements can also be used to bridge the gap between the resolution of aircraft and satellite measurements and to continuously validate the satellite measurements.

Measurements of the ice sheet height changes can be used to estimate changes in its volume and mass. This, in turn, would allow assessing the impact of this changes on global sea level, and, ultimately, on climate variability.

Changes in the ice sheet height at a particular point on a glacier are due to the snowfall changes and to changes in the ice sheet spreading rate. The changes in the snowfall occur on shorter time scales (daily) than the changes in the spreading rate (yearly). A tradeoff between the coverage and the length of observations suggests that the stratospheric balloon observations should focus on long-term changes, because they are more important and snowfall timescales are too short for the height changes to be captured over the entire region with a reasonable number (dozens) of balloons. Revisit times of less than 5 years of locations within the ice cap would be sufficient too assess changes of height due to movement of the glacier. Constellations of balloons would be able to provide the needed large-scale coverage over shorter campaign durations. Constellations may also be able to provide sufficient temporal and spatial coverage over sections of an ice cap to study snowfall rates.

The measurements are sought over an irregular grid with several kilometers of separation between the grid points to resolve the typical width of the ice stream flow within the glacier, which is of the order of tens of kilometers. Fig. 2 shows schematics of the measurement. Observations should be roughly uniform over a region to minimize interpolation errors. It is important to have a substantial number of zonal trajectories because they are more likely to capture the radial changes in spreading velocity of the glacier. The range measurements can be made with the nadir looking LIDAR. LIDAR sends a laser pulse and determines the distance by timing the return of the pulse. The required accuracy of the height determination is 2 cm (the expected change in topography is of the order of 10 cm/year). Instruments currently flown on satellites achieve this accuracy.

Instruments flown on aircraft (ATM) achieve accuracy of about 10 cm with the use of the GPS technology.

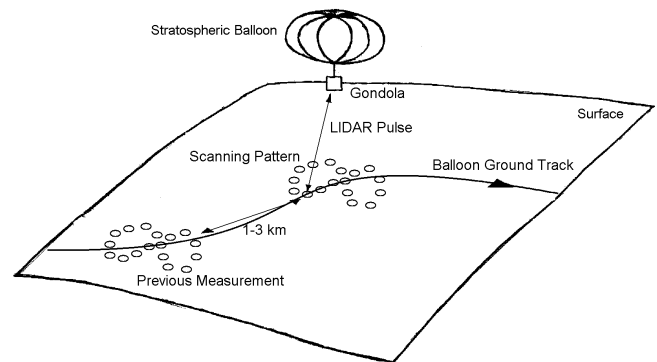


Fig. 2. Schematics of a balloon LIDAR surface topography measurements

A MOLA-type LIDAR seems to be appropriate instrument for this concept. MOLA mass is 26 kg with power consumption of 34 W. The spot size of the laser pulse on the ground depends on the altitude of the platform. For a typical angular size of tenths of milliradians (ATM, MOLA, GLAS) the laser spot on the ground for a balloon instrument at 35 km altitude would be 10 to 30 m. Along the track spacing between the measurements depends on the speed of the platform and the frequency of the observations. For a typical frequency of 10 Hz and a typical balloon speed during Antarctic summer of 1 m/s the along the tracks separation would be of the order of 0.1 m. During winter balloon speeds can rise up to 50 m/s, which would increase the separation to 5 m. Thus a balloon would be able to achieve better horizontal resolution than the needed one (several km).

The LIDAR would operate in a scanning mode. As clouds and haze are abundant in the Polar Regions it is important to be able to find a clearing in the cloud cover to acquire the surface. Scanning would allow making measurements when the surface is partially covered by clouds. Fig. 2 shows the figure eight scanning pattern. The radius of the scanning pattern that maximizes the chances of acquiring the surface would need to be determined (roughly, several kilometers wide).

Pointing control and knowledge are required to operate a LIDAR. For example, GLAS instrument has pointing control accuracy of 30 arc seconds, and the required post processing pointing knowledge is 1.5 arc seconds. Achieving required pointing accuracy on a balloon-based instrument would be the biggest challenge of the concept. For instruments flown on satellites, a star-tracking camera is used to determine the attitude with the required accuracy. Pointing control accuracy may be smaller for a stratospheric balloon due to lower speed and altitude. This star-tracking approach can potentially be implemented on a stratospheric balloon, too, because at this altitude the balloon is above the 99% of the atmosphere, at

the “edge of space” environment, and stars are clearly visible even during the day.

These and other requirements are summarized in Table I and Table II of the Appendix.

SS2) Topography of the Ice Sheet Bed

Stratospheric balloon platforms can be utilized to measure the topography of the surface underlying the ice sheets in Antarctica, Greenland or any other ice laden region using radar. Knowledge of the ice bed topography is needed to determine the speed with which the glaciers move. For example, the bed of the West Antarctic Ice Sheet lies largely below sea level. The ice sheet could potentially, in the future, become unstable, - and suddenly discharge ice from its interior into the ocean causing substantial (one meter) rise in global sea level. Presently, rapidly moving bands called ice streams are responsible for most of the ice discharge from the West Antarctic ice sheet. It is thus important to understand what determines the dynamics of the ice streams. Measuring the ice bed topography can lead to better understanding of the ice streams. Radar techniques also map internal stratigraphy of the ice sheet and thus can provide information about the past history of the flow.

Currently, measurements of the ice bed topography are made from the surface, aircraft or space. Balloon measurements would provide better coverage than the surface and aircraft observations, and better resolution than the satellite observations. Balloon observations are not affected by surface or tropospheric weather and are not limited in range, as are surface and aircraft observations. In addition, long duration balloon operations are much less expensive than the satellite operations, and are less expensive than aircraft operations.

It is desired to cover the whole region occupied by the ice sheet. The flight length should be sufficient to provide the desired coverage. Repeated or returned observations are not required as no changes in ice sheet bed topography are expected. The instrument for this concept (Radar Sounder or Ice Penetration Radar) operates by sending a signal and registering an echo. The ground footprint of the instrument is 500 by 500 m if operated from 35 km (see Fig. 3). As the balloon moves, it sweeps a 500 m wide corridor on the ground. Ideally, it is desired to have these tracks to cover the whole surface of the studied region without any gaps. However, this would require either constellations with a large number of balloons operating for long times (100 balloons for 20 years, assuming summer wind speeds of 1 m/s and no overlaps between the tracks) or continuous operations during polar night (50 balloons for 2 years, assuming wind speeds of 20 m/s during polar night and no overlaps between the tracks). It is not clear at the moment what level of the track separation would be sufficient for scientific purposes, but several kilometers (the current ground flight track separation in airborne experiments) would probably suffice. The number

of balloons required in the above estimates would then be reduced by an order of magnitude. In general, more platforms in the area would provide higher resolution. Balloon trajectory control and constellation topography management would allow for more uniform coverage.

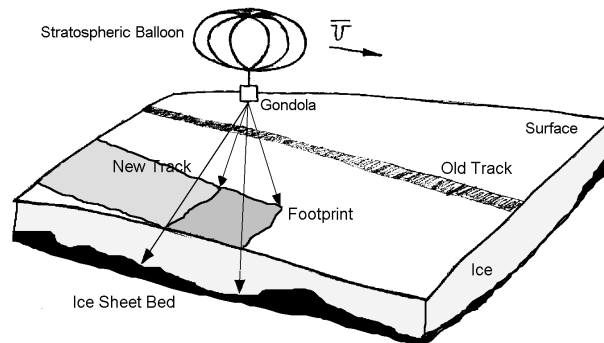


Fig. 3. Ice sheet bed topography measurement schematics

The measurement and instrument requirements for this application are summarized in Table I and Table II of the Appendix.

SS3) Earth Vector Magnetic Field Measurements

Stratospheric balloon platforms can be utilized to measure Earth's magnetic field from the stratosphere. Measuring the Earth's magnetic field from stratospheric balloon platforms offers several advantages over surface, aircraft, and satellite measurements. Even though surface measurements are made around the world by magnetic observatories, they only cover a small fraction of the Earth's surface. Systematic observations are lacking over oceans, Antarctica, Africa, South America, Siberia and other places.

Aircraft observations lack sufficient range, cannot provide global coverage and are relatively expensive. Measurements from oceanic vessels are slow and expensive. Satellite measurements are “noisy” due to ionospheric influence and require very high instrument sensitivity due to the weak field at orbital altitudes. The high orbital speed of the satellites also reduces the resolution of the measurements.

All these factors make stratospheric balloon magnetic field measurements very attractive. The balloon measurements would bridge the gap between the surface and satellite measurements; provide observations with high resolution and high signal-to-noise ratio; provide global and regional coverage; provide measurements over different time scales; and lead to development of three-dimensional maps of the Earth's magnetic field and its sources. Balloon measurements also offer an unprecedented capability to measure globally the vertical gradients of the magnetic field, which allow for better separation of magnetic field components. Observations of magnetic field variations over long time scales (years) would help to detect magma

displacements in the Earth mantle and potentially lead to forecasts of earthquake and volcanic eruptions.

Systematic observations are required globally to distinguish magnetic field variations over various spatial and temporal scales, and to separate the effects of the external component of the magnetic field (arising from interactions of the solar wind with magnetosphere), the crustal component, and the internal component of the field (due to Earth's dynamo). However there are also several focus regions that include Antarctica, active tectonic areas and coastal areas. Due to nature of the observed quantity, effective surface "footprint" is roughly equivalent to altitude of a stratospheric balloon (35 km). Because of this, maximum attainable altitude is preferred to provide maximum coverage. The footprint from a stratospheric platform is much smaller than from a satellite, but it is possible to provide global coverage from a constellation of stratospheric balloons in a reasonable period of time. For example: simple back-of-the-envelope calculations indicate that a constellation of 25 balloons can cover an area equal to the surface area of the Earth in a year (assuming no overlaps of the balloon tracks and balloons moving with stratospheric winds at representative velocity of 20 m/s).

Fig. 4 illustrates the concept. The cartoon shows a balloon flying over a region of the Earth. The dashed circle on the surface below the balloon indicates approximate area that effectively contributes to the magnetic signal at the balloon altitude h at any given moment. Subsurface sources underneath this area contribute to the signal as well. As the balloon passes over the surface, the sampled area on the ground forms a "corridor" of the width roughly equal to the balloon altitude h . This corridor is labeled as "New Track" on the figure. The instrument – a magnetometer – can be positioned on the gondola or on a tether below the gondola. Several magnetometers (at least two) would be needed for gradient measurements. They can be positioned on a tether, as is shown on the picture. A vertical separation between the sensors from 1 to 10 km is desired, with larger separation increasing the sensitivity and the resolution of the measurements.

To determine the distribution of sources that produce the measured magnetic field more accurately, observations of the same areas from different (orthogonal) directions are needed. This can be accomplished by a single balloon revisiting its previous tracks on the ground, a constellation of balloon flying in close formation, horizontally distributed magnetometers (on a long mast or a boom) on one balloon, or by two balloons connected by a long tether. The horizontal separation of balloons in a constellation observing the same area must be less than a float altitude to achieve an overlap of the ground tracks. Similarly, a single balloon revisiting the study region must closely follow its previous track or cross it often enough to provide useful data. The needed horizontal

separation of magnetometers on a single balloon is unknown at the time.

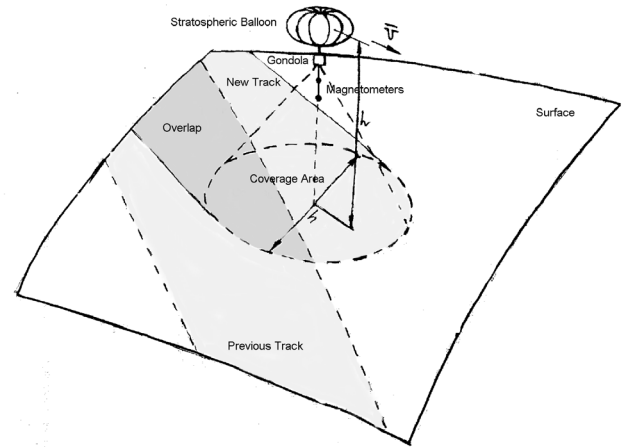


Fig. 4. Magnetic field measurement schematics

The desired length of flight is from months to years. Increasing the length of flight would provide more opportunities to revisit or to cross previous tracks (which would increase resolution of the observations), to maneuver the balloon towards the areas of interest, provide larger coverage, to separate the components of the field, and to capture long term variability of the internal magnetic field. This consideration applies to both single balloons and constellations of balloons. The frequency of the observations during a flight is 1-10 Hz, which would allow observation fluctuations of the external field.

The instrument of choice for these observations is vector magnetometer. Magnetometer measurements are simple, low-mass, low-power, and low-datarate. Knowledge of the uncertainty of the instrument attitude is required to be less than 10 arc seconds. For instruments flown on satellites, a star-tracking camera is used to determine the attitude with the required accuracy. It may be possible to implement this approach a stratospheric balloon too, since at this altitude the balloon is above the 99% of the atmosphere in "edge of space" environment and stars are clearly visible even during a day. The attitude knowledge is required for vector measurements. Note, however that it is not required for the measurements of the magnetic field strength, which would be useful by themselves.

These and other requirements are summarized in Table I and Table II of the Appendix.

SS4) 3-D Displacement Maps

Stratospheric balloon platforms can be utilized to measure Earth's surface topography using radar interferometry. Three-dimensional deformation maps created in this way can be used to monitor strain in tectonically active regions or assess topography changes associated with floods and fires. Accessibility to globally distributed focus regions would be

required from a balloon or a constellation of balloons. The length of flight depends on the ability to revisit the imaged region (see below) and also on the time scale of the changes that are to be observed. From general considerations, flight durations from months to years would be required. Certain events would require rapid response times. For example, to detect changes due to fires and floods, a platform must reach the site in a matter of days or weeks after the event. Earthquake sites can be visited in a matter of months after the event.

Two images of the same region at different viewing angles are needed to produce an interferogram and extract topography. Because of this, the subsequent ground tracks of the instrument platforms must come very close to each other, and images must overlap. Current data processing techniques require that the overflight tracks be straight lines at a constant offset from each other. The required offset is of the order of 1 km (up to 10 km).

The concept relies on the use of a radar (such as ScanSAR or SAR – Synthetic Aperture Radar). Fig. 5 shows a schematic of the concept. The radar is side looking (20-50°) and scanning. The balloon is shown with the ScanSAR antenna (15 by 1.5 m). Images are obtained by scanning the surface with different regimes that produce various coverages and resolutions. For a ScanSAR sized antenna and a balloon at 35 km, the maximum swath width is about 20 km. Smaller antenna would produce larger swath width, since the beam width is inversely proportional to the antenna size.

Interferometry requires very precise attitude knowledge (for example, 1 arc second for 500 km-altitude spacecraft illuminating at an angle of 30° – to achieve height accuracy of 2 m). For a given height accuracy the attitude knowledge precision scales proportional to altitude, thus for a balloon altitude of 35 km the attitude would need to be known to 20 arc seconds to achieve height accuracy of 2 m.

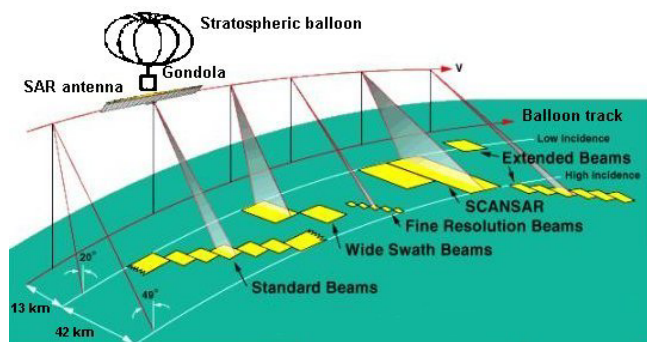


Fig. 5. Schematics of SAR observations with different regimes from a stratospheric balloon

Balloon platforms would meet significant challenges in trying to achieve straight-line trajectories and overfly small targets with the required accuracy. Hence, in the discussions of this concept with the scientist after the workshop, an opinion was formed that this concept may not be well suited

for a balloon platform. However, if two horizontally separated antennas can be flown on a single platform, the concept may still make sense for a balloon platform. The length of the mast would probably need to be of the order of meters or tens of meters. Antennas can also be separated vertically, with one antenna at the gondola and the other one hanging on a tether below the balloon. Another option is to fly balloons in tandem, but the straight-line trajectory problem still remains.

The requirements for this concept are summarized in Table I and Table II of the Appendix

B. Atmospheric Radiation (AR)

AR1) Radiative Fluxes at the Top of the Atmosphere (TOA)

Stratospheric balloon platforms can be utilized to measure radiative fluxes at the TOA. These measurements can be used to validate radiative flux estimates based on satellite measurements or they can be used independently for long-term monitoring and observation of the dynamics of radiative fluxes. At present, the CERES (Clouds and Earth Radiant Energy System) instruments on EOS Terra satellite make continuous measurements of outgoing short and long-wave radiation from the Earth. However, CERES instruments measure radiances, directionally dependent radiation from a source location on the Earth. These radiance measurements must be converted to fluxes at the top of the atmosphere to estimate the Earth's energy budget. The conversion process introduces 4% uncertainties into flux estimation, which can be large enough to affect the interpretation of the measured data. For example, 4% error in long wave flux estimation corresponds to an error of about 10 W/m². Even 1 W/m² change in radiative forcing is important for climate change, and variability of 4 W/m² could drive a major climatic change. Stratospheric balloons can measure the TOA fluxes directly, thereby eliminating the conversion error and providing a significantly better estimate of the earth radiation budget. A sufficiently large constellation of balloons can provide nearly global coverage (see Fig. 6). Smaller regional constellations can be used to validate satellite measurements and to test the feasibility of a global constellation

Knowledge of the Earth's radiative budget (the amount of energy received from the Sun, the amount of energy emitted into space, and their difference) is crucial for determining (a) whether or not the global climate is changing and (b) what is the direction of the changes, if they are occurring.

The preferred coverage for this observation is global, however, regional coverage (for example, tropics) is acceptable at early stages of constellation deployment or for proof of concept mission. The minimum length of observations is 2 weeks with continuous observations reported every 2 minutes. Longer flight durations are desired. The measurements must be performed simultaneously with the overpassing CERES instrument for satellite data validation with temporal accuracy of 1 minute. The slow-

moving balloons will be overflowed at least twice a day by the CERES instrument on a near-polar sun-synchronous orbit, no matter where they are on the Earth surface.

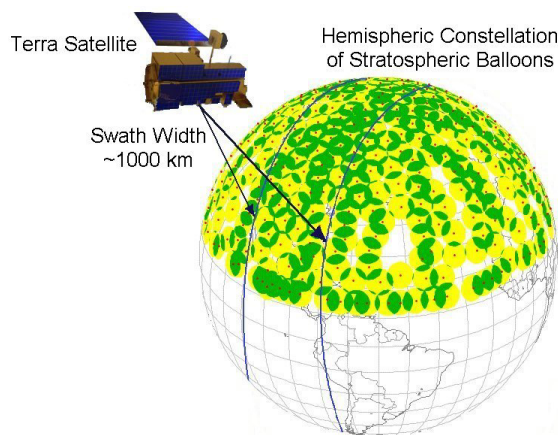


Fig. 6. Hemispheric constellation of 395 stratospheric balloons. Red dots represent balloons, yellow circles - the limb-to-limb viewing areas of balloons, green regions - overlaps of viewing areas. Also shown for comparison a single track of CERES instrument. The satellite swath width is of the order of 1000 km.

The Active Cavity Radiometer proposed for these measurements is a low-mass and low-power instrument. ACRs would measure short-wave ($0 \rightarrow 5 \mu\text{m}$) and “total” ($0.2 \rightarrow 20 \mu\text{m}$) fluxes. The long wave flux ($5 \rightarrow 20 \mu\text{m}$) would be obtained by differencing the total and short-wave measurements. The wide field instrument would be insensitive to pointing (within reason) because it measures hemispheric flux (from 2π -space below the balloon). The narrow view instrument would need accurate knowledge of pointing (less than a degree). Position knowledge of the platform is required to correlate balloon measurements with the satellite measurements and with the map. Trajectory control may be required to position the platform over target regions.

These and other requirements are summarized in Table I and Table II of the Appendix.

C. Atmospheric Chemistry (AC)

AC1) Vertical Profiles of Ozone and Trace Constituents

Stratospheric balloon platforms can be utilized for remote and *in situ* measurements of vertical profiles of temperature, pressure, ozone, water vapor, and tracer elements (such as CO_2 , CO , CH_4 , N_2O , etc.) in tropical regions. A combination of three payloads was discussed for these measurements: a fixed *in situ* payload on a tether and (or) vertically-translating gondola, a remote sensing payload on a gondola, and meteorological dropsondes. Different payloads can be carried on different platforms, flying in proximity to each other to sample the same region of the atmosphere, or each platform can carry the same combined payload.

The tropical region plays an important role in global climate system and in ozone chemistry. It is currently understood that troposphere air enters the stratosphere in tropics. This region of the tropical atmosphere, where tropospheric air enters the stratosphere and remains substantially unmixed with midlatitude stratospheric air is usually referred to as the “tropical pipe”. The low temperature of the tropical tropopause limits the amount of water that enters the stratosphere. Water vapor can significantly affect global energy balance by (a) blocking the long wave emission from escaping the Earth and (b) by increasing the number of stratospheric clouds that reflect solar radiation. Troposphere air entering the stratosphere also carries with it antropogenically produced elements (such as CFC’s) that affect ozone chemistry. The proposed measurements would thus help to characterize tropospheric-stratospheric exchange and “tropical pipe” boundaries.

AC1.1) In situ payload. The *in situ* payload would measure vertical profiles of ozone and tracer elements, together with temperature, pressure and water vapor profiles with *in situ* sensors at altitudes between 15 and 30 km on seasonal and interannual scales. Three balloons would circumnavigate the globe in the equatorial region (within 14°S and 14°N latitudinal band). The balloons are not required to fly in formation. The desire is to get more or less uniform coverage within the band. The minimal requirement on flight duration is to complete one orbit (about 20 days at 20 m/s at the equator). The observations would be repeated every 2 or 3 month. This flight sequence must be continued for several years to capture interannual variability (for example, 5 years to capture two cycles of QBO - Quasi-Biennial Oscillation). Alternatively, a single balloon flight of very long duration would be sufficient. It is desired to make observations continuously during a flight. The required vertical coverage is between 15 km and the altitude of the balloon (25-35 km). Although observations at higher altitudes are desirable, observations up to 35 km are acceptable. The required vertical resolution of the measured profiles is from 100 to 500 m. The *in situ* observations are required to coincide in space and time with the remote observations (see below). Due to the nature of the proposed remote instrument (FTIR, see below) that employ a solar occultation technique, simultaneous observations are possible twice a day, during sunrise and sunset.

The *in situ* instruments could be positioned on a tether and reeled up and down to provide measurements over the required height of the atmosphere. Another option is an ascending/descending (with vertical velocity of 3-5 m/s) balloon platform with a fixed instrument suite on the gondola. Another implementation option for the *in situ* payload is multiple instruments positioned along a tether.

The *in situ* instruments for the proposed concept already exist. However, technological advances reducing mass and power consumption of *in situ* instruments are desired, since

the existing instruments are heavy (200 kg) and require a lot of power (800 W). Some instruments of the *in situ* payload require frequent calibration (every measurement) using calibration gases.

AC1.2) Remote sensing payload. The concept for remote sensing observations is similar to that for *in situ* observations. 3 circumnavigating balloons are suggested in the equatorial region. The desired vertical coverage for the remote sensing instrument is from tropopause (15 km) to 35 km. The instrument is positioned at 35 km.

The proposed instrument is a modified JPL Fourier Transform Infrared Radiometer (FTIR) MkIV. The FTIR is a solar occultation instrument; it makes measurements of the atmospheric abundances by measuring the absorption of the sunlight (see Fig. 7). It requires a suntracer to track the sun at sunset and sunrise. MkIV was successfully flown on a stratospheric balloon during NASA SOLVE mission.

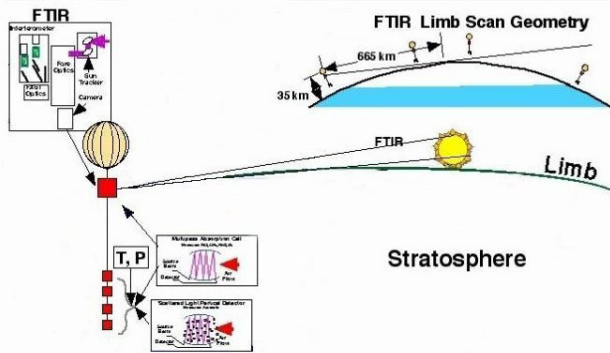


Fig. 7. Schematics of the *in situ* and remote sensing payloads operations on a stratospheric balloon

AC1.3) Meteorological dropsondes. The meteorological measurements, valuable by themselves, will compliment the *in situ* and remote measurements. The measurements would cover an atmospheric column from the altitude of the balloon (35 km) to the surface. The required vertical resolution of these observations is 0.5-1 km.

The concept assumes the use of dropsondes. Between 0 and 5 drops per day are required. GPS dropsondes currently used for meteorological measurements weigh 400 g and are designed to operate in a temperature range between -90° to +60° C.

The requirements for this concept are summarized in Table I and Table II of the Appendix.

III. NEXT STEP

The mission requirements and instrumentation specifications comprising the set of science requirements for stratospheric platforms will be used to develop a preliminary technology development roadmap. Fig. 8 shows the process by which we are moving from key Earth science questions and measurements to a balloon platform technology roadmap.

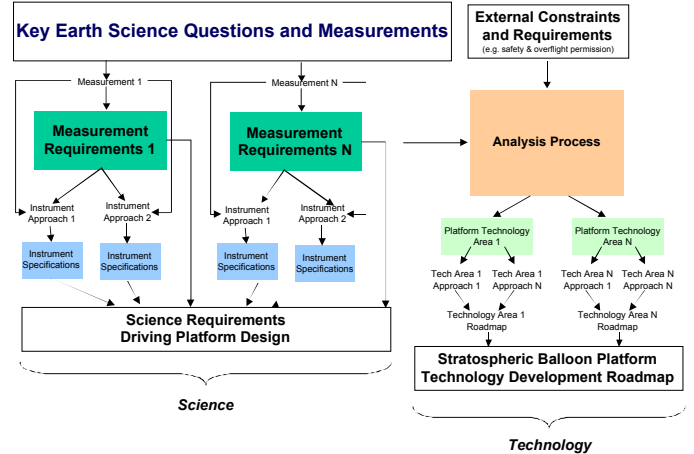


Fig. 8. Stratospheric Balloon Platform Technology Development Roadmap Process

Combination of science requirements and external constraints and requirements (for example, safety and overflight permission) comprise the “pool” of performance requirements. For each requirement a set of technologies needed to satisfy this requirement can be defined (for example, to achieve global coverage, technologies for trajectory control, long-term power supply, communications, etc., would be need) together with technology trade offs (for example, requirements for power supply can be satisfied either with onboard power generation approach or with onboard power storage approach). Requirements can be ranked based on their impact on achieving application success. The relevant technologies would then receive higher rankings too. Several technologies with the highest rankings would be chosen based on this analysis (indicated by the Analysis Process box on Fig. 8). Different approaches to implement those technologies would be studied (for example, precision payload landing technology may rely on development of parafoils or, alternatively, on development of propulsion systems). Technology roadmaps for each identified technology area would be developed. Together they will comprise the stratospheric balloon technology roadmap.

IV. CONCLUSIONS

We described several potential Earth science applications for the new class of guided stratospheric balloon platforms. Stratospheric balloon platforms have capabilities that can make possible revolutionary new approaches in Earth sciences and further our understanding of the global Earth system. We developed a set of performance requirements based on input from Earth scientists that drives the development of technology requirements. We outline the method by which we will move from the set of requirements towards the development of the technology roadmap. For the remainder of this activity, we will be developing preliminary roadmaps for each technology area and combining them into an overall stratospheric balloon platform technology development roadmap.

APPENDIX

These tables summarize measurement (Table I) and instrument (Table II) requirements developed for the applications described in the paper. The first column lists all the measurement and instrument parameters, while the first row gives the applications names. The requirements are found at the intersection of the applications columns and parameter rows.

Table I
MEASUREMENT REQUIREMENTS

Measurement Parameters	<i>SSI</i> Ice Surface Topography	<i>SS2</i> Ice Bed Topography	<i>SS3</i> Magnetic (gravity) fields	<i>SS4</i> Deformation Maps	<i>ARI</i> TOA Fluxes	<i>AC1</i> Ozone and tracers profiles
Horizontal coverage	Antarctic, Greenland ice sheets; other ice caps	Antarctic, Greenland ice sheets; other ice caps	Global; focus areas are Antarctica, active tectonic areas, coastal regions	Access to globally distributed locales	Global or regional (tropics)	Tropics, between 10±4° S and 10±4° N
Horizontal resolution	Several km (1-3)	Several km track separation; ideally, overlapping 500 m wide tracks	Overlap in ground track (35 km wide).	Constant separation (1-10 km) of ground tracks (30 km wide)		
Vertical coverage			Maximum balloon altitude to maximize surface footprint			From 15 km up to balloon altitude (AC1.1, AC1.2); From the balloon altitude down to the surface (AC1.3)
Vertical resolution			From 1 to 10 km for vertical gradient measurements			100-500 m (AC1.1); 2 km (AC1.2); 1-2 km (AC1.3)
Length of observations	Sufficient for full coverage of desired area, up to 5 years	Sufficient for coverage; one-time observation	Continuous; from months to years	Continuous; from months to years	Minimum 2 weeks	1 orbit flight duration (20 days), every 2 to 3 months, for 5 years.
Frequency of observations	1-10 Hz	1 Hz	1-10 Hz (to capture external field fluctuations)	Continuous	Every 2 min	Continuous (every 10-100 s) (AC1.1); 1 hour during sunset and sunrise (AC1.2); Up to 5 drops a day (AC1.3)
Simultaneity		Simultaneous with satellites	Instantaneous measurements along the vertical gradient		With overflying CERES instrument	Simultaneous FTIR/ <i>in situ</i> measurements during sunset/sunrise

Table II
INSTRUMENT SPECIFICATIONS

Instrument Parameters	<i>SS1</i> Ice Surface Topography	<i>SS2</i> Ice Bed Topography	<i>SS3</i> Magnetic (gravity) fields	<i>SS4</i> Deformation Maps	<i>ARI</i> TOA Fluxes	<i>AC1</i> Ozone and tracers profiles
Mass	30 kg	1 to 5 kg plus antenna (Sounder); 30 kg (Radar)	1 kg	50 kg	0.5kg	200 kg (AC1.1); 350 kg (AC1.2); 40 kg (AC1.3)
Power consumption	34 W continuous	30 W max (includes processing) (Sounder); 100 W peak; battery use at night (Radar).	2 W continuous	10-20 W	0.5 W	800 W (AC1.1); 250 W (AC1.2); 400 18 V batteries (AC1.3)
Consumables						Calibration gases
Thermal regime	10° to 25° C	-50° to 50° C (Sounder); From -20° to 40° C, 25° C preferred (Radar)	-55° to 40° C	10 to 25° C	25±10° C (needs to be heated)	20±5° C (AC1.1); -90° to +60° C (AC1.3)
Environmental regime			Sensitive to EMI, requires magnetically clean platform (0.3-1 m boom)			Avoid contamination by balloon (AC1.1)
Pointing and position accuracy	Attitude control to better than 30 arc seconds Attitude knowledge to better than 1.5 arc seconds Vertical position knowledge to better than 2 cm	Attitude control to better than 0.5 radian Position knowledge to 1 m (Sounder); Platform attitude knowledge, instrument pointing knowledge and instrument pointing control to better than few degrees (Radar).	Attitude knowledge to better than 10 arc seconds. Position knowledge within GPS technology limits	Attitude knowledge to better than 1 arc seconds. Position knowledge within GPS technology limits.	Wide field insensitive to pointing; narrow field – within a degree or better	Knowledge of position within GPS technology limits
Mobility					May require tilting for solar calibration	Reel down on a tether (AC1.1); scanning (AC1.2).
Configuration	Nadir looking; scanning	Nadir looking	May require positioning sensors on a tether or on a long boom (mast)	May require positioning instruments on a tether or on a long boom (mast)		Side-looking (AC1.2)
Calibration	Infrequent, 3-4 times per campaign; over sea surface, corner reflectors	Infrequent via ground transmitter/receiver	Infrequent; over control areas, or after flight termination	Via ground truth	Few times in 2 weeks; by looking at sun/space; or after flight termination on recovery	Some instrument require frequent calibration (AC1.1)
Data handling	100s bps	50 bytes/sec; 5Mbytes/day onboard processing (Sounder); Onboard processing; 10Kbytes/sec (Radar)	1-2 Mbytes/day. Latency not an issue	Gbytes/day	84 Kbytes/day	350 kbps for 1 hour during sunset/sunrise (AC1.2)
Coordination	Coordination with satellites for validation, complimenting data sets.	Coordination with satellites for validation; within constellation to achieve track overlap	Coordination to achieve surface “footprint” overlap may be required for high-resolution observations.	Coordination to achieve surface “footprint” overlap or constant separation (1-10 km) and straight-line trajectories is required.	Coordinate observations with CERES overflight.	Simultaneous <i>in situ</i> , remote and meteorological measurements